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Evaluation of Selected Thermal Control Coatings for Long-Life Space Structures

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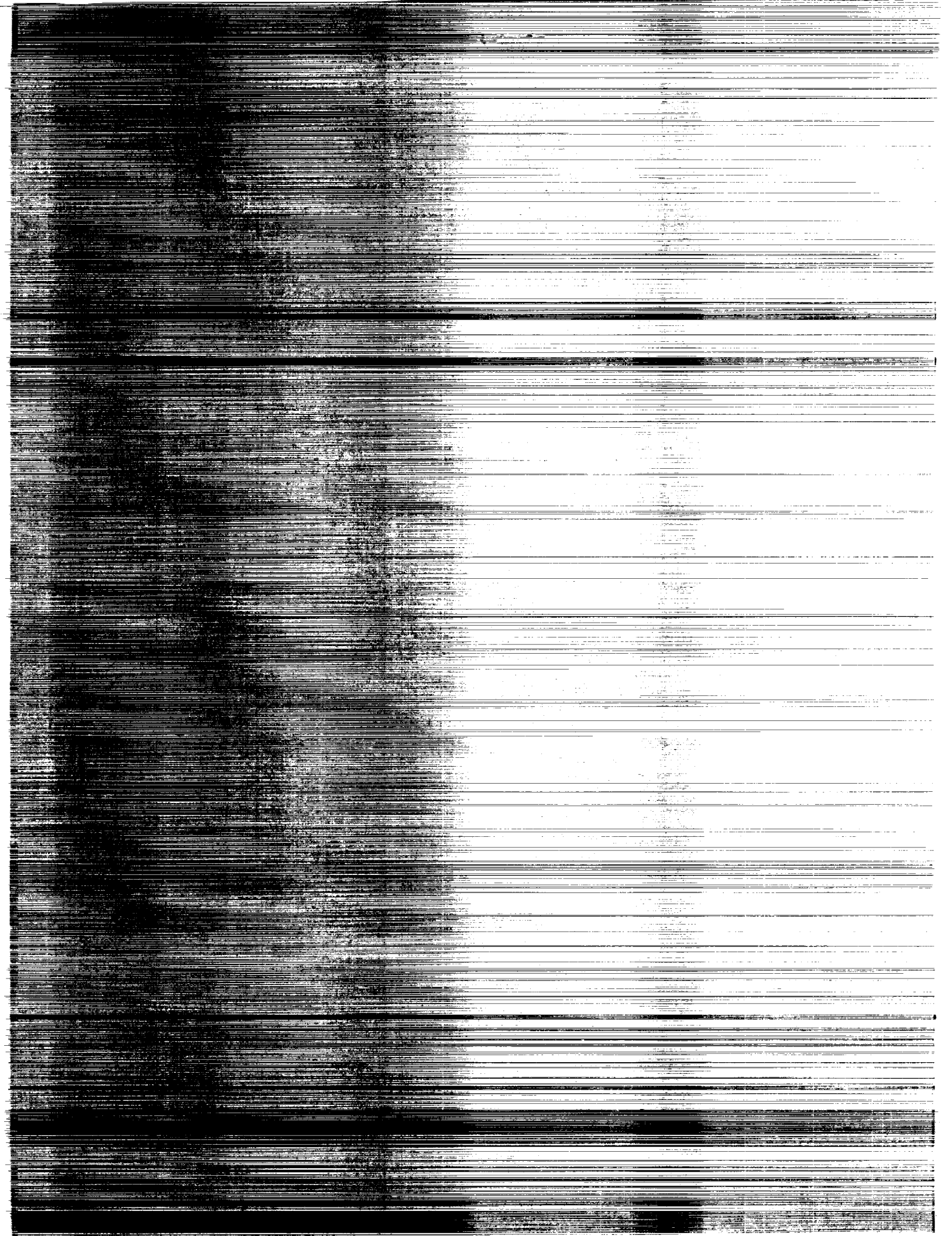
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Abstract

Graphite-reinforced resin matrix composites are currently being considered for spacecraft structural applications because of their light weight, high stiffness, and low thermal expansion. These materials must, however, be protected against degradation caused by the various elements of the natural space environment. Thin protective coatings with stable optical properties which minimize orbital thermal extremes are attractive for this purpose. One way to accomplish this objective is to apply protective coatings which have the proper ratio of solar absorptance (α_s) to thermal emittance (ϵ).

Research at Langley Research Center has concentrated on the development of sputtered coatings applied directly to the graphite/epoxy (Gr/Ep) composite surface and on anodized thin aluminum foil. Both coating systems can be used as an atomic oxygen barrier between the graphite-reinforced resin matrix composite and the natural space environment as well as for thermal control mechanisms. A small additional effort was also made to develop nickel-based coatings which could be applied directly to the composite. These coating systems were selected for study over commercial white paints because their inherent tenacity made them more attractive from a reliability standpoint for long-life space missions.

Of all the protective coating techniques described, anodized aluminum foil coatings are clearly the leading candidates for use on tubular and flat composite structures for large platforms in low Earth orbit. The anodized foil provides the composite substrate material with protection against many of the elements of the natural space environment—atomic oxygen, ultraviolet and particulate radiation—and can offer a broad range of tailored α_s/ϵ . Both the aluminum foil and the anodizing process are commercially available, and the foil can be produced in the large quantities required for large space structures.

Introduction

Graphite-reinforced resin matrix composites are currently being considered for spacecraft structural applications because of their attractive features—light weight, high stiffness, and low thermal expansion. These materials must, however, be protected against degradation caused by the various elements of the natural space environment. Thin protective coatings are attractive for this purpose, but these coatings, whatever their nature, must have stable optical properties which minimize the thermal extremes to which the composite structure is subjected as the spacecraft moves in and out of the Earth's shadow.

One way to accomplish this objective is to apply protective coatings which have the proper ratio of solar absorptance (α_s) to thermal emittance (ϵ).

The thermal control coatings program at Langley Research Center has focused on the development of stable thermal control coatings for composite (largely graphite/epoxy) structures (tubes and panels) for long-life space platforms in low Earth orbit (LEO). Research has concentrated on the development of sputtered coatings applied directly to the graphite/epoxy (Gr/Ep) composite surface and on anodized thin aluminum foil. Both coating systems can be used as an atomic oxygen barrier between the graphite-reinforced resin matrix composite and the natural space environment. A small additional effort was also made to develop nickel-based coatings which could be applied directly to the composite.

Sputtered, anodized, and nickel-based coatings were selected for study over commercial white paints because their inherent tenacity made them more attractive from a reliability standpoint for long-life missions. White paints have been used on many spacecraft with acceptable space environmental stability over 3- to 5-year missions (refs. 1 and 2), but no data are available for extremely long-life (30-year) missions. To avoid possible chipping or discoloration of paint coatings, several tenacious chemically bonded coatings were chosen for more intensive study. The purpose of this paper is to describe results from research conducted on these tenacious coatings, which were expected to be substantially more adherent than paints or adhesively bonded coatings, and which met certain solar absorptance and thermal emittance criteria.

Selection Criteria for Spacecraft Temperature Balance

Temperature cycling occurs as a spacecraft orbiting the Earth at low altitude proceeds from sunlight to Earth shadow approximately every 90 minutes. An unpublished computer-generated heat transfer analysis for graphite/epoxy tubular structures in a typical spacecraft orbit resulted in figure 1. The figure shows temperature cycling range as a function of the ratio of solar absorptance (α_s) to thermal emittance (ϵ). The ideal case is illustrated by the 0.25/0.25 ratio, where the temperature cycle is around room temperature and extremely small compared with the temperature cycle of the uncoated graphite/epoxy tube with a ratio of 0.85/0.85. The values of 0.25/0.25 are not always achievable by each coating process and do not provide latitude for degradation of α_s (increase in α_s values) due to environmental exposure and spacecraft contamination. For

30-year missions, a solar absorptance of 0.30 and a thermal emittance of 0.65 were selected to be nominal values for initial thermal control, which would permit extensive degradation of the coating before temperatures (-70 to $+170^{\circ}\text{F}$) similar to those of the uncoated composite would be reached. Coating systems which could meet these thermal criteria were then selected for further study on the basis of tenacity and ability to act as atomic oxygen barriers. These systems are discussed in the remainder of the paper.

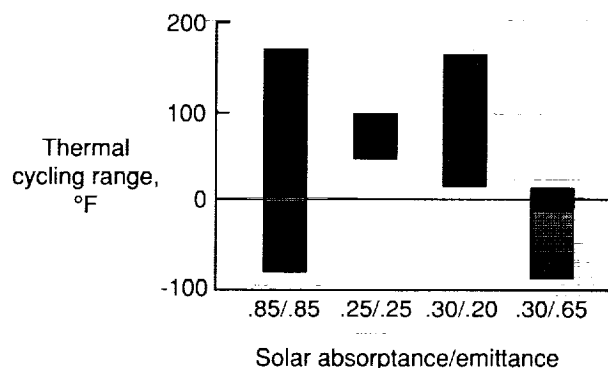


Figure 1. Thermal cycling range for spacecraft truss structure (assuming 2-in-id Gr/Ep tubes as truss elements).

Sputter-Deposited Aluminum

The sputtering study (ref. 3) consisted of magnetron sputtering of aluminum on graphite/epoxy substrates. This study was driven by the same previously mentioned thermal analysis which showed that an uncoated graphite/epoxy surface could experience temperature cycles from -70 to $+170^{\circ}\text{F}$, often inducing microcracking. Details of specimen preparation and sputtering conditions are presented in appendix A.

Optical reflectance generally decreases with surface roughness, thereby increasing α_s . In the case of composite laminates, surface roughness is controlled mainly by the texture of the caul plates, separation sheets, and bleeder cloths used during fabrication. The fabrication procedure employed in this study produced a laminate that had a "rough" side with an average roughness of $170\text{ }\mu\text{in.}$ and a "smooth" side with an average roughness of about $25\text{ }\mu\text{in.}$, as measured by a profilometer. Specimens of both surface finishes were sputter coated with aluminum for different lengths of time, resulting in coating thicknesses ranging from 420 to $2520\text{ }\text{\AA}$.

Solar absorptance and total normal emittance were determined for six coating thicknesses and two surface textures. The results obtained are presented

in table I and figures 2 through 4. These results indicate that sputter coating of the composite substrate dramatically lowers α_s from an undesirable value of about 0.70 to a much more desirable value of 0.16 on the smooth surface (fig. 2). Coating of the substrate beyond $420\text{ }\text{\AA}$ appears to have little effect on α_s , at least up to the maximum thickness of $2520\text{ }\text{\AA}$. Although the α_s values for the rough surfaces are somewhat higher, i.e., about 0.24 , this, too, is an acceptable value for space flight in LEO. However, the sputtered aluminum coating also lowers ϵ from 0.8 for the smooth surface of the bare composite to 0.08 (fig. 3), an unacceptably low value for effective temperature balance in space. This problem could have been anticipated because the sputtered surface is a highly reflective, conductive metal. The aluminum-coated rough surface, however, produces a thermal emittance of 0.2 to 0.3 (fig. 3), yielding an α_s/ϵ ratio of about 1 (fig. 4), which is acceptable under some space flight conditions.

The lower α_s and ϵ values obtained for the smooth surfaces (as compared with rough surfaces) can be attributed to two effects. First, sputtered coatings on rough surfaces tend to be nonuniform, with thinner coatings deposited on highly sloped surfaces than on flatter surfaces. Second, with uniform rates of deposition per unit area across the planetary plate, rough specimens and smooth ones of the same diameter receive equal amounts of sputtered material. Calculations of surface area based on the roughness data indicate that the rough specimens present about 1.3 times as much surface area as the smooth ones. The coating will therefore be thinner on rough substrates than on smooth ones, and the effect of the coating on optical properties will therefore be reduced.

For the rough surfaces the minimum α_s occurred at around $1000\text{ }\text{\AA}$ of aluminum (see fig. 2); for the smooth surfaces the minimum occurred at less than $400\text{ }\text{\AA}$. At greater coating thicknesses, solar absorptances generally remained constant, although there is the hint of slight increases out to about $2520\text{ }\text{\AA}$. Oxidation of the aluminum during sputtering may have caused these slight increases, since electron dispersive X-ray analysis of the coatings shows the presence of oxygen. The decrease of emittance with increasing aluminum coating thickness, to the point of aluminum opacity, was expected (fig. 3). The ratio of α_s/ϵ is approximately 1 for the rough surfaces and increases slightly with coating thickness (fig. 4). The α_s/ϵ ratio for the smooth surfaces (fig. 4) rises from 2 to 4 over the coating thickness range of 420 to $2520\text{ }\text{\AA}$. Use of these coatings on composites in large space structures in LEO would have limited

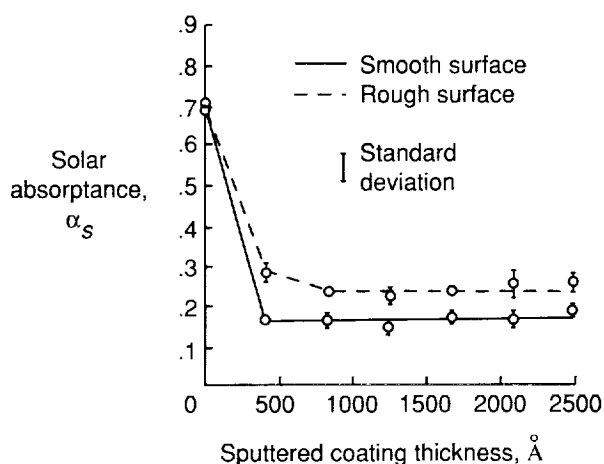


Figure 2. Solar absorptance of sputtered aluminum on T300/5209 as a function of sputtered coating thickness.

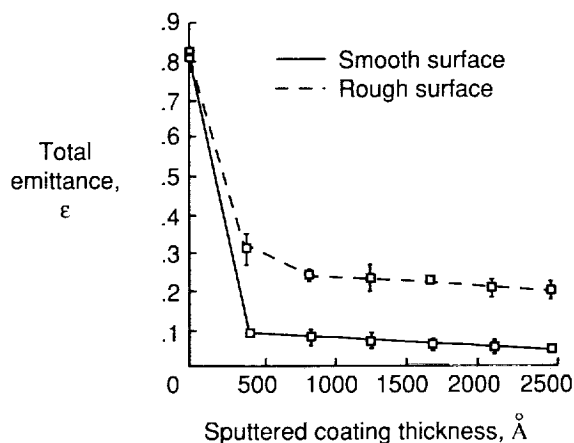


Figure 3. Total normal emittance of sputtered aluminum on T300/5209 as a function of sputtered coating thickness.

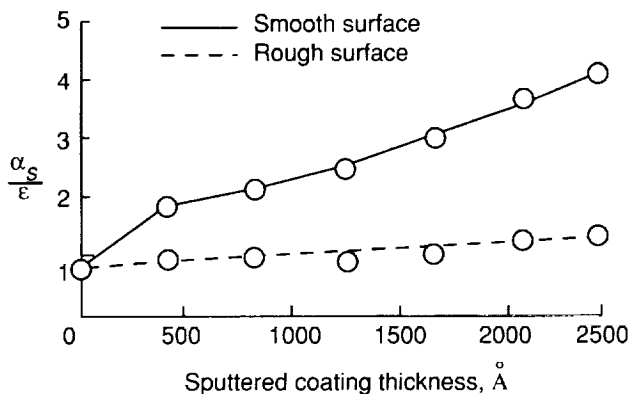


Figure 4. The ratio α_s/ϵ of sputtered aluminum as a function of coating thickness on T300/5209.

application, due to lack of uniformity and complexity of application.

Nickel-Based Coatings

An investigation was launched by Composite Optics, Inc. into ways in which the surfaces of a proprietary nickel-based moisture barrier coating could be altered to provide desirable spectral characteristics for LEO applications. The coating offered an excellent method of protecting a composite substrate against atomic oxygen attack but α_s was 0.2 and ϵ was 0.1, an undesirable combination for the intended applications in space. Coating material composition, mechanical abrasion, and chemical oxidation of the surface were investigated as potentially viable techniques by which to raise α_s to about 0.3 and ϵ to about 0.6.

Alterations in surface preparation and nickel plating composition proved fruitless in raising ϵ . Alterations to the specularity of the surface were the most effective way to alter ϵ , and values of 0.2 to 0.35 were obtained. Unfortunately, α_s was also altered to a fairly high (and undesirable) value of 0.5 or more. Based on these results, the decision was made to cease further consideration of this coating system. The final report (COI-0988-5769, Sept. 21, 1988) on this effort contains proprietary information and was given extremely limited distribution.

Chromic Acid Anodizing

A series of contractual studies (refs. 4 and 5) was established to develop and then optimize chromic acid anodizing (CAA) applications for large platforms in LEO. CAA techniques were developed for foil 24 ft long, 8 ft wide, and 3 mil thick. This foil was then slit into 8-in-wide pieces 24 ft long, the size required to protectively wrap the longest struts on the then-proposed Space Station *Freedom*. Details of CAA procedures and the development of anodized aluminum foil coatings are given in appendix B.

The 1145-H19 Al alloy was the only alloy evaluated that achieved the desired optical goals of a solar absorptance of 0.35 or less and a thermal emittance of 0.55 to 0.70. The 1145 foil also was the only high-purity foil readily available in a variety of thicknesses and tempers. The fully hardened temper (H19) minimizes chances of wrinkling and creasing of the foil during processing, while the half-hard temper (H24) was the easiest to work with when wrapping Gr/Ep tubes. Optical properties achievable by this process are given in table II.

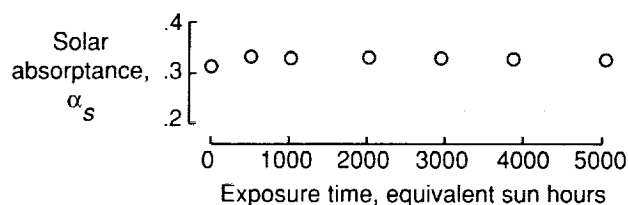


Figure 5. Effects of ultraviolet radiation (2 times equivalent sun hours; zero air mass) on the solar absorptance of water-sealed anodized 3-mil, 1145 Al foil.

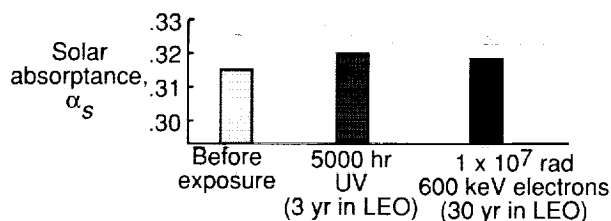


Figure 6. Effects of ultraviolet and electron radiation on anodized aluminum foil.

Sealing the surface of the anodized foil by submerging it in hot water through which an electrical current was passed was performed to increase resistance to soiling and staining during handling. The sealing process is easily performed and possesses a side benefit of increasing emittance while the absorptance remains constant.

CAA of foil 25 ft long by 44 in. wide was accomplished with up to three pieces of foil being processed at the same time. Uniformity of optical properties throughout the 25-ft lengths was excellent. A process specification was developed and included as an appendix in reference 5.

The anodizing techniques developed were used in the fabrication of Al foil-covered 2-in-diameter graphite/epoxy (T-300/934 and P75/934) tubes. Both cocuring and adhesive bonding of the Al were used. The chromic-acid-anodized Al foil graphite/epoxy system was evaluated for durability to the LEO space environment. For example, ultraviolet radiation exposure in a vacuum, using xenon short-arc lamps with quartz envelopes producing wavelengths of 200–400 nm for 5000 equivalent sun hours (equivalent to 3 years in LEO), resulted in an increase of less than 0.01 in solar absorptance (see fig. 5). Also, no disbonding or change in optical properties occurred after 25 000 thermal cycles of $\pm 150^\circ\text{F}$ in dry nitrogen (simulating 3 years in LEO). In addition, radiation exposure of 10^7 rads with 600-keV electrons (equivalent to 30 years in LEO) resulted in a negligible change in solar absorptance (see fig. 6). Preliminary, as yet unpublished, results from the Long Duration

Exposure Facility confirm minimal changes in physical and optical properties of thin anodized aluminum after almost 6 years in LEO.

Summary of Results

Several tenacious thermal control coating systems which met certain thermal, adherence, and atomic oxygen resistance criteria were chosen from intensive study as potential coverings for composite tubes on long-life space platforms in low Earth orbit (LEO). The results of these studies indicated the following:

1. Chromic-acid-anodized 3-mil-thick 1145-H19 Al adhesively bonded to Gr/Ep tubular structures was shown to provide excellent protection and thermal control in the LEO environment. The anodized foil protected the Gr/Ep from degradation caused by atomic oxygen (see appendix B), minimized the temperature gradients in the composite struts, and provided passive thermal control. Techniques were successfully developed for anodizing foil large enough to wrap, as a single piece, around diagonal struts of large truss structures.
2. Sputtering directly onto composites proved to be only a marginally successful method of providing a surface within the desired range of the ratio of solar absorptance to thermal emittance (α_s/ϵ) and, at best, will be of limited use.
3. Nickel-based coatings, like all metallic materials, offer excellent protection against various elements of the space environment, and can readily be mass produced, but have inherently low values of ϵ . Preliminary efforts to find methods to alter the spectral characteristics were unsuccessful.

Of all the protective coating techniques described, anodized aluminum foil coatings are clearly the leading candidates for use on tubular and flat composite structures for large platforms in low Earth orbit. The anodized foil provides the composite substrate material with protection against many of the elements of the natural space environment—atomic oxygen, ultraviolet and particulate radiation—and can offer a broad range of tailored α_s/ϵ . Both the aluminum foil and the anodizing process are commercially available, and the foil can be produced in the large quantities required for space platforms.

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Appendix A

Sputtering Study for Aluminum on Graphite/Epoxy

Test Specimen Description

The specimens were 1-in-diameter discs of 8-ply [0,0,0,90]_s T300/5209 graphite/epoxy composite material cut from laminates. The laminate was fabricated from unidirectional commercial prepreg. The laminate was laid-up on a smooth surface Teflon caul plate with a standard textured bleeder cloth on top, so that the cured composite had a smooth side and a rough side. Peak-to-trough measurements of the surface profile on the smooth surface were in the range of 20 to 80 μin . The surface profile of the rough surface yielded peak-to-trough measurements of up to 1600 μin . in variation, with the average being 170 μin .

Specimen Preparation

After the specimens were cut from the sheet, they were lightly sanded around the edges with SiC paper to remove projecting fibers and were then wiped with trichloroethane and rinsed with deionized water. They were stored for several weeks in a desiccator. The specimens were weighed before and after sputter coating in an attempt to determine coating weights, but the results were inconclusive because of the extremely low masses of the coatings.

Sputter Conditions

Six sputter coating runs were made. For each run, ten 1-in-diameter specimens were placed on a plate in the vacuum chamber. A sapphire thickness monitor was placed in the center of the plate, and arranged around it were five specimens with the

smooth side up and five with the rough side up. During sputtering, the plate was stationary, about 3 in. under the aluminum target.

All coatings were sputtered at 1 kW power. The sputtering chamber was evacuated for at least 30 minutes before sputtering, resulting in initial chamber pressures in the range of 4×10^{-6} to 1×10^{-5} torr. The chamber was backfilled with argon to a pressure of 8 μm and an arc was struck to form a plasma. The system was programmed to ramp up power to reach 1 kW in 1 minute after the plasma formed. At that moment, the large fan valve shielding the specimens from the plasma was opened to expose the specimens. When the desired sputtering time was achieved, the valve was closed and power was turned off. The sputtering times were based on previous experience and were chosen to provide a range of coating thicknesses. The thicknesses of aluminum deposited on the sapphire thickness monitors were assumed to be the same as the coatings on the specimens.

Optical Properties

Solar reflectance was measured in the wavelength range of 0.3 to 2.5 μm with a Gier Dunkle MS-251 solar reflectometer. The source, optics, and sphere characteristics of this instrument as it was used approximate the solar spectrum. For an opaque surface, the solar absorptance can be computed by subtracting the reflectance from unity. Total normal emittance of the specimens was determined from infrared reflectivity measurements made with a Gier Dunkle DB-100 infrared reflectometer in the wavelength range of 5 to 25 μm . For each surface texture and coating thickness, five specimens were coated and measured.

Appendix B

Development of CAA Aluminum Foil Coatings

Anodizing Procedures

The anodizing of the Al foil was performed using various contractor-developed specifications and production facilities. The specifications also include the cleaning of the foil, which is required to ensure a satisfactory anodizing. The specifications required that the foils be anodized in the following sequence:

1. Vapor degreased
2. Placed in racking
3. Alkaline cleaned
4. Hot water rinsed
5. Deoxidized
6. Cold water rinsed
7. Anodized
8. Cold water rinsed
9. Dried (warm air)
10. Sealed with hot water

After the foil was vapor degreased, a metal rack was clamped to the perimeter of the foil to provide a secure electrical contact. The racking was kept to a minimum because the foil under the racking does not anodize. This unanodized portion is trimmed off after the anodizing process is completed. The racking also provides a means for handling the foil during the various cleaning processes performed prior to the anodizing. Sections of Al foil (1 ft²) were anodized and, after the anodizing was complete, 1-in² samples were cut from the 1-ft² sections to determine the optical values. This established the control optical values that could be achieved by following the anodizing parameters of the specifications. Follow-up samples were then fabricated using modified anodizing parameters in an attempt to achieve the target optical values.

Aluminum Foil Selection

The foil selection study was limited to evaluating Al foils that could be procured "off the shelf," because extremely large orders are required to procure nonstandard foils. Four Al foil alloys with various tempers were available for evaluation as described below. The desired thickness was 3 mils, which was the lightest weight Al foil that could be handled consistently without damage during the CAA processing

of the 125-ft-long foils. The Al foil alloys and tempers which were evaluated are 3-mil 1145-H19 and 1145-H24, 3-mil 5024-H19, 3-mil 3003-H19, and 5-mil 6061-0. They possessed similar solar absorptances of 0.08 to 0.17 and thermal emittances of 0.02 prior to anodizing. The variation in absorptance values was caused by sample orientation (because of the striations in the unanodized foil) and was not attributable to alloying elements. Alloy 1145 was the most readily available of all the Al foil alloys. It was available as fully soft (1145-0), half-hard (1145-H24), or fully hardened temper (1145-H19) and in a variety of thicknesses. Alloy 6061 is fairly common but is rarely produced in thicknesses less than 5 mils. The other alloys were not as readily available.

Initial Screening

The CAA parameters varied were (1) immersion time in chromic acid solution, (2) anodizing voltage (22 or 40 V), (3) ramp time to desired voltage, and (4) hot deionized water sealing. It was not possible to vary the chromic acid solution percentage of 7 percent (by weight), because the CAA was performed in tanks being used for the production of aircraft parts. Previous work (ref. 3) showed minimal changes in α_s and ϵ of CAA aluminum as a result of changing the chromic acid solution from 7.5 percent to 5 percent as other parameters remained constant.

The two alloys that underwent extensive experimentation were 1145 and 6061. The 5024 and 3003 were available in limited quantities only and therefore underwent limited characterization. The solar absorptance and emittance values as a function of CAA parameters, for all foils evaluated, are shown in tables II, III, IV, and V. Examination of the results from reference 4 shows that

1. Immersion time and anodizing voltage had the greatest impact on the optical values. The 1145 alloy anodized at 22 V, 5-minute ramp, and 50-minute immersion at full voltage achieved the targeted optical values (see table II). Increasing the voltage to 40 V and decreasing the immersion time to 35 minutes also achieved similar optical values.
2. CAA of 6061 did not achieve the targeted optical values (see table III). The solar absorptance was too high (approximately 0.50) after foils were immersed long enough to achieve the minimum targeted emittance of 0.55. Limited testing showed 5024 and 3003 alloys (tables IV and V) to possess similar traits. Absorptance values for 6061 were approximately 40 percent higher than 1145 when anodized at the same parameters.

3. Single immersions of the foil in hot deionized water sealing had minimal effects on absorptance, but increased the emittance an average of 9–12 percent over unsealed samples, when other parameters remained constant. This effect was more noticeable at shorter immersion times.

Optimization

The 3-mil 1145-H19 and/or 1145-H24 Al foil exposed for 50 minutes at 22 V or 35 minutes at 40 V, both with a ramp time of 5 minutes, were selected as the optimum foil and anodizing parameters for the following reasons:

1. Alloy 1145 was the only alloy evaluated that achieved the targeted optical properties.
2. Alloy 1145 foil at 3 mils was the only alloy readily available “off the shelf.” This alloy foil is primarily available in the H19 temper (fully hardened), but also can be purchased in the H24 temper (half-hard). The fully hardened temper minimizes the chances of wrinkling and creasing of the foil during processing, but the H24 temper is the easiest to work with when wrapping Gr/Ep tubes.

Other Important Features

Varying the anodizing parameters of the CAA process permits optical tailoring of the anodized foil. However, once the foil reached an emittance of 0.55 and a solar absorptance of 0.35, no further major changes in optical properties occurred.

Hot deionized water sealing prevented staining during handling and was easily performed. A side benefit of sealing was an increase in emittance with no increase in absorptance.

The nonspecularity provided by foils that met the required emittance and absorptance goals was sufficient to eliminate the need for surface pretreatment prior to anodizing, thereby reducing processing time and cost.

Smut

Anodized foils immersed for the 35–50 minutes required to achieve the desired emittance exhibited an olive-green tint that darkened with immersion time. Achieving the minimal targeted emittance of 0.55 while not exceeding the targeted solar absorptance of 0.35 was difficult because of darkening of the foil. Tests were performed to determine if the darkening was caused by smut forming on the foil during the anodizing process (and therefore preventable) or if it was inherent to the CAA process. Three different anodizing process lines were used, each of which

used a different deoxidizer. All tests proved negative for smut, an indication that the olive-green tint was inherent to the CAA process.

Specularity

In a truss structure configuration, multiple reflection from the highly specular anodized aluminum foil could lead to hot spots on payloads or structural elements during solar exposure. Hence, emphasis was placed on obtaining the desired optical properties with a nonspecular reflecting anodized aluminum foil. Figure B1 illustrates the reduction in specular reflectance obtained from the use of the chromic acid anodizing process. The solar absorptance of these foils was 0.31 to 0.34, with emittance values ranging from 0.63 to 0.72.

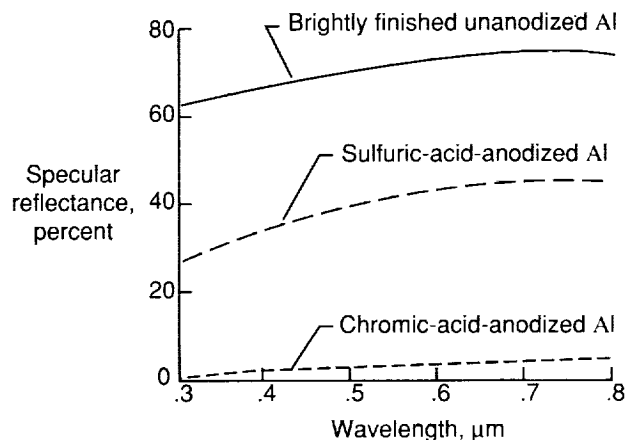


Figure B1. Specular reflectance of some chemically treated aluminum foils.

Atomic Oxygen Testing

To determine if short-term exposure to atomic oxygen (AO) caused changes in optical properties or mass loss, 1-in-diameter discs of unsealed anodized Al foil were tested. The discs were exposed for 48 hours in an AO materials screening facility. The flux was approximately 40 to 400 times orbital rates, depending on sample location. A key difference between the AO facility and orbital conditions is the thermal energies of the oxygen atoms. In the lab facility, they were approximately 0.1 to 0.2 eV, but in orbital collisions they are approximately 5 eV. The 48 hours of exposure in the lab delivered a fluence of approximately 7×10^{21} oxygen atoms/cm² to the sample surface. There was no change in either solar absorptance or emittance of the four samples and no mass loss. During the 48 hours of exposure a reference material of 2-mil-thick Kapton exhibited approximately 12–15 percent mass loss.

Anodizing of Large Area Foils

A rack was designed and constructed to anodize foil up to 25 ft long. Successful demonstrations were conducted on 1145-H19, 1145-H24, and 6061-0 foils. Uniformity of optical properties throughout the 25-ft

lengths was excellent, and the targeted optical values were achieved. Unsealed foils had a solar absorptance of 0.31 and a thermal emittance of 0.60 to 0.64; sealed foils had a solar absorptance of 0.33 and an emittance of 0.67. No wrinkling or creasing of the foils occurred when handled properly.

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Table I. Solar Absorptance and Thermal Emittance of Sputtered Aluminum on Composite Surfaces

Coating thickness, Å	Smooth			Rough		
	α_s	ϵ	α_s/ϵ	α_s	ϵ	α_s/ϵ
Uncoated	0.694	0.805	0.862	0.704	0.815	0.863
420	.164	.087	1.894	.286	.301	.959
840	.169	.079	2.208	.244	.235	1.041
1260	.157	.064	2.550	.232	.229	1.023
1680	.179	.059	3.094	.252	.225	1.120
2100	.173	.048	3.714	.270	.220	1.359
2520	.193	.046	4.254	.272	.193	1.410

Table II. Solar Absorptance and Thermal Emittance of Chromic Acid Anodizing of 1145-H19 Aluminum Foil

Anodizing parameters				Optical results				
Anodizing voltage, V	Ramp time to full voltage, min	Immersion time at full voltage, min	Hot deionized water sealed (Yes/No)	Solar absorptance, α	Thermal emittance, ϵ	α/ϵ		
22	5	25	No	0.23	0.31	0.74		
↓	5	30	↓	.24	.37	.65		
	5	35		.32	.47	.66		
	5	40		.35	.51	.69		
	5	45		.35	.54	.65		
	5	50		.34	.57	.60		
	10	20		.17	.05	3.40		
	10	30		.31	.44	.70		
	10	40		.34	.54	.63		
	15	25		.15	.03	5.00		
	15	30		.34	.49	.69		
	15	35		.35	.48	.73		
	15	40		.36	.55	.65		
	5	10		.24	.16	1.50		
	5	15		.25	.21	1.19		
	5	20		.29	.33	.88		
	5	25		.35	.45	.78		
	5	30		.38	.51	.75		
	5	35		.38	.56	.68		
	5	40		.39	.55	.71		
	5	45		.39	.57	.68		
	5	50		.39	.57	.68		
	↓	↓		25	Yes	.38	.56	.68
				30	↓	.39	.58	.67
				35		.38	.58	.66
				40		.39	.61	.64
45				.39	.62	.63		
50				.39	.62	.63		

Table III. Chromic Acid Anodizing of 6061 Aluminum Foil

Anodizing parameters				Optical results		
Anodizing voltage, V	Ramp time to full voltage, min	Immersion time at full voltage, min	Hot deionized water sealed (Yes/No)	Solar absorptance, α	Thermal emittance, ϵ	α/ϵ
40 ↓	5 ↓	10	No ↓	0.48	0.18	2.67
		15		.47	.28	1.68
		20				
		25		.48	.50	.96
		30		.50	.55	.91
		35		.52	.61	.85
		40		.54	.63	.86
		45		.50	.60	.83
		50		.55	.63	.87
		10	Yes ↓	.47	.18	2.67
		15		.50	.29	1.72
		20		.49	.39	1.26
		25		.49	.56	.88
		30		.51	.65	.78
		35		.54	.68	.79
		40		.54	.68	.79
		45		.55	.68	.81
		50		.57	.69	.83

Table IV. Chromic Acid Anodizing of 5024 Aluminum Foil

Anodizing parameters				Optical results		
Anodizing voltage, V	Ramp time to full voltage, min	Immersion time at full voltage, min	Hot deionized water sealed (Yes/No)	Solar absorptance, α	Thermal emittance, ϵ	α/ϵ
40 ↓	5 ↓	25	No ↓	0.29	0.26	1.12
		30				
		35		.29	.31	.94
		40		.44	.45	.98

Table V. Chromic Acid Anodizing of 3003 Aluminum Foil

Anodizing parameters				Optical results		
Anodizing voltage, V	Ramp time to full voltage, min	Immersion time at full voltage, min	Hot deionized water sealed (Yes/No)	Solar absorptance, α	Thermal emittance, ϵ	α/ϵ
40	5	25	No	0.44	0.43	1.02
↓	↓	30	↓	.43	.46	.93
		35		.47	.58	.81
		40				

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13. ABSTRACT (Maximum 200 words) Graphite-reinforced resin matrix composites are being considered for spacecraft structural applications because of their light weight, high stiffness, and lower thermal expansion. Thin protective coatings with stable optical properties and the proper ratio of solar absorptance (α_s) to thermal emittance (ϵ) minimize orbital thermal extremes and protect these materials against space environmental degradation. Sputtered coatings applied directly to graphite/epoxy composite surfaces and anodized coatings applied to thin aluminum foil were studied for use both as an atomic oxygen barrier and as thermal control coatings. Additional effort was made to develop nickel-based coatings which could be applied directly to composites. These coating systems were selected because their inherent tenacity made them potentially more reliable than commercial white paints for long-life space missions. Results indicate that anodized aluminum foil coatings are suitable for tubular and flat composite structures on large platforms in low Earth orbit. Anodized foil provides protection against some elements of the natural space environment - atomic oxygen, ultraviolet, and particulate radiation - and offers a broad range of tailored α_s/ϵ . The foil is readily available and can be produced in large quantities, while the anodizing process is a routine commercial technique.				
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